APPENDIX C
RFI PHASE I MONITORING WELL BORING LOGS AND WELL CONSTRUCTION DIAGRAMS

BORING LOG | HALLIBURTON NUS

PROJECT: ALLIED SIGNAL, FRANKFORD PLANT | BORING NO.: MW-101
PROJECT NO.: 3814 | DATE: 1-16-92 | DRILLER: BRIAN DEVINE
ELEVATION: | FIELD GEOLOGIST: R. GOOD
WATER LEVEL DATA:
(Date, Time & Conditions)

SAMPLE NO. & TYPE	DEPTH (ft.) OR RUN NO.	BLOWS 6" OR RQD (%)	SAMPLE RECOVERY / SAMPLE LENGTH	LITHOLOGY CHANGE (Depth, ft.)	SOIL DENSITY/CONSISTENCY OR ROCK HARDNESS	COLOR	MATERIAL CLASSIFICATION (MATERIAL DESCRIPTION*)	ROCK BR. OR USCS	REMARKS
	0.0					GRAY & BRN	ASPHALT, CRUSHED STONE, SILT, CLAY, GRAVEL, PEBBLES, SOME MISC FILL MAT'L → WOOD, RUBBER SCRAPS, ETC.		0 PPM DRY TO DAMP FILL
	4.0					LT. GRAY	CEMENT GROUT 3.5 FT TO 4.0 FT		
S-1 @ 1145	6.0	35 25 15 12	24"/24"			LT. GRAY BRN & BLK	16" CEMENT GROUT; 8" ASH, GRAVEL, CLAY, SILT, GLASS		0 PPM FR/S-1 DAMP TO MOIST FILL
S-2 @ 1150	8.0	5 4 2 2	0"/24"			N.A.	NO RECOVERY – AUGER SILT, CLAY, GRAVEL, NUMEROUS GLASS FRAGS, SMALL TO >1"		0 PPM FR/S-2 ROCK WEDGED IN OPENIN WATER ON SPOON
	9.0								
S-3 @ 1202	11.0	5 5 3 2	8"/24"	----	LOOSE	BLK & LT GRAY BRN	7" GLASS FRAGMENTS, SILT, CLAY, TRACE BRICK FRAGS; 1" WELL SRT FGR TO MGR SAND	SW	0 PPM FR/S-3 SATURATED FILL & POSS ALLUVIUM
	13.0								
S-4 @ 1215	15.0	12 9 7 10	20"/24"		MED DENSE	DARK GRAY	10" SAND, CLAY, GRAVEL, ROUNDED PEBBLES - POORLY SORTED; 10" WELL SORTED MGR SAND	GC; SW	0 PPM FR/S-4 SATURATED, ALLUVIUM
	16.5								

REMARKS AUGER TO 4 FT; SAMPLE TO 8 FT; AUGER TO 9 FT; SAMPLE TO 11 FT; AUGER TO 13 FT; SAMPLE TO 15 FT; AUGER TO 16½ FT (OVER DRILL SLIGHTLY TO FACILITATE WELL INSTALLATION)
USE 4¼ IN I.D. / 8" O.D. HOLLOW STEM AUGERS TO DRILL, SAMPLE & INSTALL WELL

BORING MW-101

PAGE 1 OF 1

* See Legend on Back

BORING LOG — HALLIBURTON NUS

PROJECT: ALLIED SIGNAL FRANKFORD PLANT
BORING NO.: MW - 102
PROJECT NO.: 3814
DATE: 1-17-92
DRILLER: BRIAN DEVINE
ELEVATION:
FIELD GEOLOGIST: R. GOOD
WATER LEVEL DATA :
(Date, Time & Conditions)

SAMPLE NO. & TYPE	DEPTH (ft.) OR RUN NO.	BLOWS 6" OR RQD (%)	SAMPLE RECOVERY SAMPLE LENGTH	LITHOLOGY CHANGE (Depth,ft.)	MATERIAL DESCRIPTION* SOIL DENSITY/ CONSISTENCY OR ROCK HARDNESS	COLOR	MATERIAL CLASSIFICATION	ROCK BR. OR USCS	REMARKS
	0.0					BRN	FILL: SILT, CLAY, SAND, BRICK GRAVEL, WOOD, ETC		5 PPM, DAMP, FILL
									REFER TO LOG OF NEARB BORING NO 22 FOR DESCRIPTION OF OVER-BURDEN MATERIAL
	4.0								
S-1		7					UPR 6" FILL AS ABOVE		0 PPM FR/S-1
		9				BRN	LWR 18" CLAY TO SILTY CLAY	CL	DAMP
@ 0835	6.0	14	24"/24"		MED. DENSE		TO FGR SAND W/ SOME CGR	SP	FILL/ALLUVIUM
		14					SAND & PEBBLES		
	9.0								
S-2		19			DENSE TO	BRN	POORLY SORTED SILT, FGR-CGR	SM	0 PPM FR/S-2
@ 0853	11.0	32	24"/24"		V. DENSE		SAND, ROUND TO SUBROUNDED	GM	DAMP TO MOIST
		29					PEBBLES OF VARYING SIZE		ALLUVIUM.
		31							
	14.0								
S-3		7				BRN	INTERBEDDED, POORLY SORTED	SM	
		8			MED.	TO	FGR-CGR SAND W/ GRAVEL &	GM	0 PPM FR/S-3
@ 0904	16.0	8	24"/24"		DENSE	GRAY	VARYING SIZE PEBBLE & TRACE		SATURATED
		10					OF SILT & CLAY		ALLUVIUM.
							LWR 5" WELL SRT FGR SAND	SW	
	19.0								
S-4		13				BRN	2" WELL SRT FGR SAND THEN	SW	0 PPM FR/S-4
		21			DENSE TO	TO	PR. SRT FGR-CGR SAND, GRAVEL		SATURATED
@ 0920	21.0	25	20"/24"		V. DENSE	GRAY	VARIOUS SIZE PEBBLES, SMALL	SP/GP	ALLUVIUM
		29					COBBLES		
	22.0								

REMARKS: AUGER & SAMPLE EVERY 5 FT TO TOTAL DEPTH. WATER FOUND AT APPX 13 FT. OVERDRILL TO 22 FT TO ACCOMODATE WELL INSTALLATION DUE TO HEAVING SAND W/IN AUGERS.

BORING MW-102

PAGE 1 OF 1

* See Legend on Back

BORING LOG

HALLIBURTON NUS

PROJECT: ALLIED SIGNAL, FRANKFORD PLANT
BORING NO.: MW-103
PROJECT NO.: 3814
DATE: 1-17-91
DRILLER: BRIAN DEVINE
ELEVATION:
FIELD GEOLOGIST: R. GOOD
WATER LEVEL DATA: APPX 6½ FT
(Date, Time & Conditions)

SAMPLE NO. & TYPE	DEPTH (ft.) OR RUN NO.	BLOWS 6" OR RQD (%)	SAMPLE RECOVERY SAMPLE LENGTH	LITHOLOGY CHANGE (Depth, ft.)	MATERIAL DESCRIPTION* SOIL DENSITY/ CONSISTENCY OR ROCK HARDNESS	COLOR	MATERIAL CLASSIFICATION	ROCK BR. OR USCS	REMARKS
	1.0					GRAY	CRUSHED STONE, SOME SAND, SILT, CLAY		DRY TO DAMP, FILL
S-1 @ 1110	3.0	16 / 14 / 14 / 13	20"/24"			BLK GRAY & RED	CRUSHED STONE, SILT, CLAY, ASH, CEMENT, BRICK, WOOD, GLASS, COAL		2.8 PPM FR/S-1 DAMP, FILL SLIGHT NAPTHALENE ODOR
S-2 @ 1112	5.0	7 / 4 / 3 / 3	3"/24"			BLK GRAY & RED	SAME AS ABOVE		1.3 PPM FR/S-2 MOIST TO WET, FILL
S-3 @ 1120	7.0	2 / 2 / 2 / 2	24"/24"			BLK GRAY & RED	SAME AS ABOVE		1.2 PPM FR/S-3 DAMP TO SATURATED IN LWR 8", FILL
	9.0								
S-4 @ 1130	11.0	10 / 15 / 25 / 40	24"/24"			BLK	6" FILL AS ABOVE 18" HARD TAR OR ASPHALT-LIKE SUBSTANCE W/ FINE FRAGMENTS OF SAND, BRICK, CLAY & MISC FILL. POSS TRACES OF NAPTHALENE		220 PPM FR/S-4 MOIST, FILL POSS. SOLVENT ODOR
	14.0								
S-5 @ 1144	16.0	2 / 2 / 2 / 2	20"/24"			BLK	WOOD, BRICK, SILT, SAND, CLAY ASH - CLAY LAYER NEAR BASE BLACK SLURRY OR MUD AT BOTTOM OF SPOON - BUBBLING		80 PPM FR/S-5 SATURATED FILL - ALL WATER IN SOME LAYER, ALL OIL IN OTHERS

REMARKS: AUGER TO 1 FT; SAMPLE TO 7 FT; AUGER TO 9 FT; SAMPLE TO 11 FT; AUGER TO 14 FT; SAMPLE & AUGER TO 16 FT & INSTALL WELL - APPX WATER LEVEL 6½ FT BASED ON SAMPLES

BORING MW-103

PAGE 1 OF 1

* See Legend on Back

HALLIBURTON NUS
Environmental Corporation

MONITORING WELL SHEET

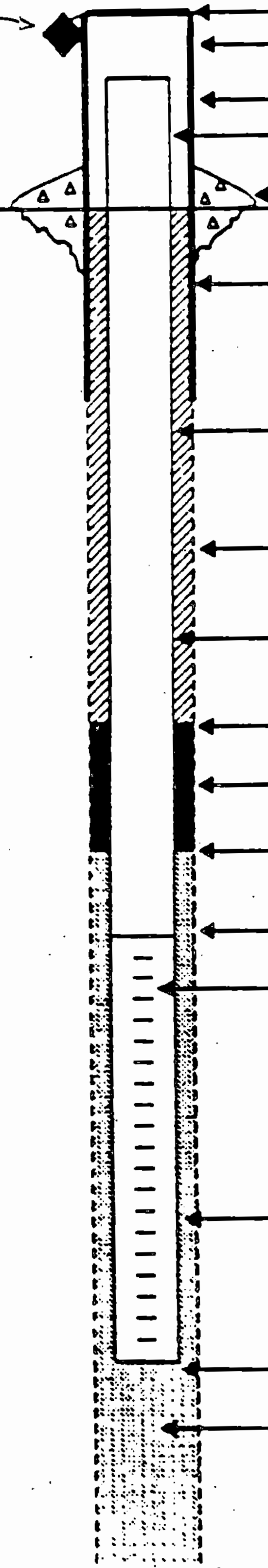
PROJECT: Allied Signal
PROJECT NO.: 3814
ELEVATION:
FIELD GEOLOGIST: Robert Good

LOCATION: Phila., PA
BORING: MW - 101
DATE: 1 - 16 - 92

DRILLER: Brian Devine
DRILLING: Delta Well & Pum
METHOD: H.S.A.
DEVELOPMENT METHOD: Bailer

American Lock Co.
Key no. 09276

GROUND ELEVATION



ELEVATION OF TOP OF SURFACE CASING:
ELEVATION OF TOP OF RISER PIPE:
STICK - UP TOP OF SURFACE CASING: Flush mount
STICK - UP RISER PIPE: 1' 3/4" bgs.
TYPE OF SURFACE SEAL: Cement grout
I.D. OF SURFACE CASING: 8 in
TYPE OF SURFACE CASING: Steel
RISER PIPE I.D. 2 in.
TYPE OF RISER PIPE: Stainless steel
BOREHOLE DIAMETER: 8 in
TYPE OF BACKFILL: Cement grout
ELEVATION / DEPTH TOP OF SEAL: 2'
TYPE OF SEAL: Bentonite pellet
DEPTH TOP OF SAND PACK: 4'
ELEVATION / DEPTH TOP OF SCREEN: 6' 3/4" b.g.
TYPE OF SCREEN: Stainless Steel (Johnson)
SLOT SIZE x LENGTH: 0.010 in slot size
I.D. OF SCREEN: 2"
TYPE OF SAND PACK: Morie no. 1 quartz sand
ELEVATION / DEPTH BOTTOM OF SCREEN: 16' 3/4" b.g.
ELEVATION / DEPTH BOTTOM OF SAND PACK: Appx 16' b.g.
TYPE OF BACKFILL BELOW OBSERVATION WELL: Caved material of sand, gravel and pebbles
ELEVATION / DEPTH OF HOLE: 16' 1/2" b.g.s

HALLIBURTON NUS
Environmental Corporation

MONITORING WELL SHEET

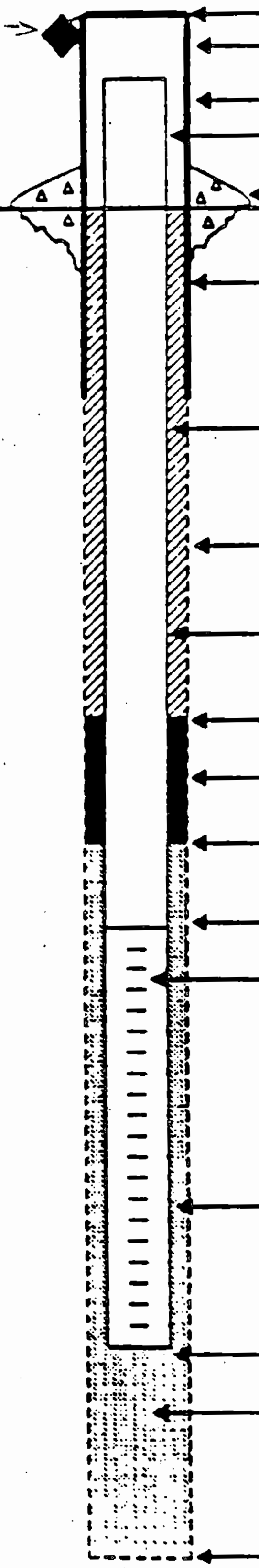
PROJECT: ALLIED SIGNAL
PROJECT NO.: 3814
ELEVATION:
FIELD GEOLOGIST: ROBERT GOOD

LOCATION: PHILA., PA
BORING: MW - 102
DATE: 1-17-92

DRILLER: BRIAN DEVINE
DRILLING METHOD: DELTA WELL & PUM H.S.A.
DEVELOPMENT METHOD: BAILER

American Lock Co.
Key no. 09276

GROUND ELEVATION



ELEVATION OF TOP OF SURFACE CASING:
ELEVATION OF TOP OF RISER PIPE:
STICK - UP TOP OF SURFACE CASING: Flush mou
STICK - UP RISER PIPE: 1' 1½" b.g.
TYPE OF SURFACE SEAL: Cement grout
I.D. OF SURFACE CASING: 8 in.
TYPE OF SURFACE CASING: Steel
RISER PIPE I.D. 2"
TYPE OF RISER PIPE: Stainless steel
BOREHOLE DIAMETER: 8"
TYPE OF BACKFILL: Cement grout
ELEVATION / DEPTH TOP OF SEAL: 5' b.g.s.
TYPE OF SEAL: Bentonite pellet
DEPTH TOP OF SAND PACK: 7' b.g.s.
ELEVATION / DEPTH TOP OF SCREEN: 11' 1½" b.g.s.
TYPE OF SCREEN: Stainless steel (Johnson)
SLOT SIZE x LENGTH: 0.010 in. slot size
I.D. OF SCREEN: 2"
TYPE OF SAND PACK: Morie no. 1 sand, quartz
ELEVATION / DEPTH BOTTOM OF SCREEN: 21' 1½" b.g.
ELEVATION / DEPTH BOTTOM OF SAND PACK: Appx 21' 1½"
TYPE OF BACKFILL BELOW OBSERVATION WELL: "Caved" natural material of sand, pebbles & small cobbles
ELEVATION / DEPTH OF HOLE: 22'

HALLIBURTON NUS
Environmental Corporation

MONITORING WELL SHEET

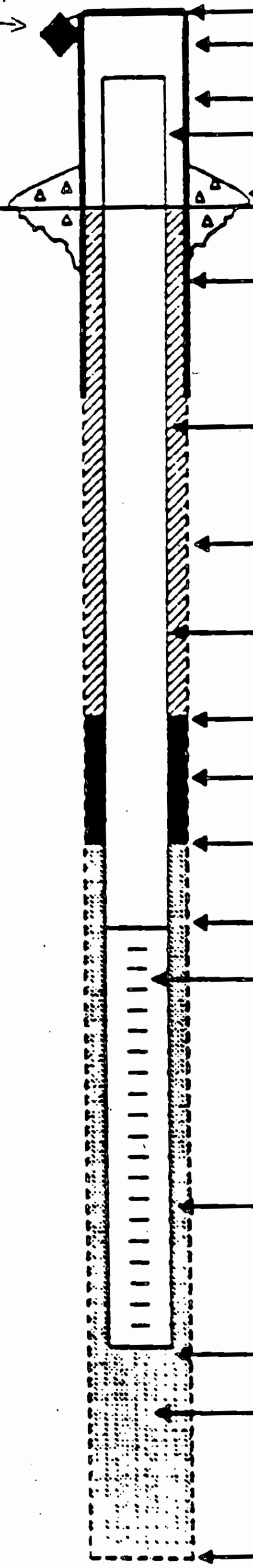
PROJECT ALLIED SIGNAL
PROJECT NO. 3814
ELEVATION
FIELD GEOLOGIST ROBERT GOOD

LOCATION PHILA, PA
BORING MW-103
DATE 1-17-92

DRILLER BRIAN DEVINE DELTA WELL & PUMP
DRILLING METHOD H.S.A.
DEVELOPMENT METHOD BAILER

American Lock Co.
Key no. 09276

GROUND ELEVATION



ELEVATION OF TOP OF SURFACE CASING :
ELEVATION OF TOP OF RISER PIPE:

STICK - UP TOP OF SURFACE CASING: Flush mount
STICK - UP RISER PIPE : 8½" b.g.s

TYPE OF SURFACE SEAL: Cement grout

I.D. OF SURFACE CASING: 8"
TYPE OF SURFACE CASING: Steel

RISER PIPE I.D. 2"
TYPE OF RISER PIPE: Stainless steel, Threaded flush joint

BOREHOLE DIAMETER: 8"

TYPE OF BACKFILL: Cement grout

ELEVATION / DEPTH TOP OF SEAL: 1' b.g.s.

TYPE OF SEAL: Bentonite pellet

DEPTH TOP OF SAND PACK: 3' b.g.s.

ELEVATION / DEPTH TOP OF SCREEN: 5'8½" b.g.s

TYPE OF SCREEN: Stainless steel (Johnson)

SLOT SIZE x LENGTH: 0.010" slot size

I.D. OF SCREEN: 2"

TYPE OF SAND PACK: Morie no. 1 sand, quartz

ELEVATION / DEPTH BOTTOM OF SCREEN: 15'8½" b.g.

ELEVATION / DEPTH BOTTOM OF SAND PACK: Appx 16' b.g.s
TYPE OF BACKFILL BELOW OBSERVATION WELL: Fill material in place - wood, brick, ash, silt, sand, clay

ELEVATION / DEPTH OF HOLE: 16' b.g.s

APPENDIX D
SLUG TEST CALCULATIONS

<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>

A Q T E S O L V

A Program for
Automatic Estimation of Aquifer Coefficients
From Aquifer Test Data

By:

Glenn M. Duffield
and
James O. Rumbaugh, III

Geraghty & Miller Modeling Group
1895 Preston White Drive, Suite 301
Reston, VA 22091

(703) 476 - 0335

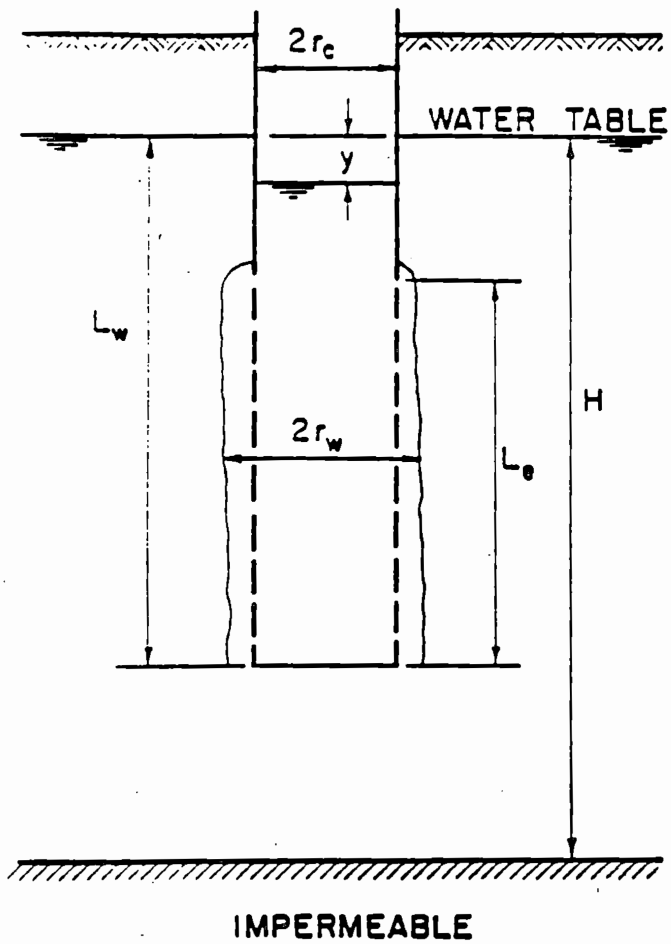
A Q T E S O L V is a user-friendly program designed to analyze data from aquifer tests automatically. Aquifer coefficients for a variety of aquifer test conditions can be estimated by A Q T E S O L V , including the following:

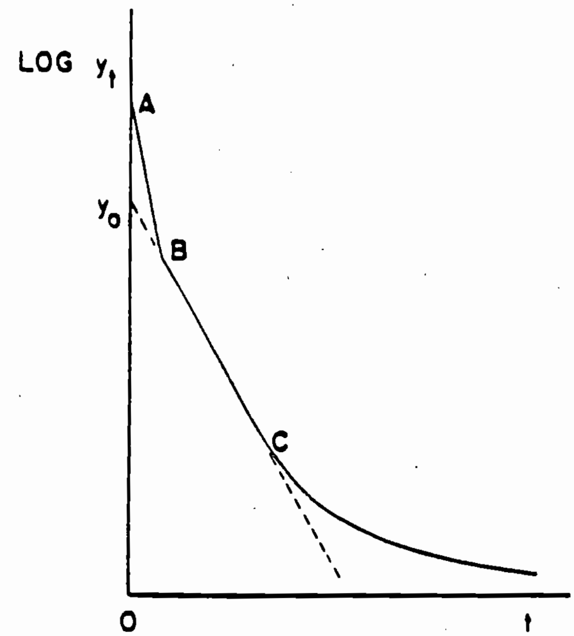
- confined aquifers, unconfined aquifers, and leaky aquifers
- pumping tests, injection tests, recovery tests, and slug tests

Features:

- Interactive, menu-driven program design
- Nonlinear least-squares estimation of aquifer coefficients
- Statistical analysis of results

2. BOUWER-RICE DEFINITION SKETCHES





Schematic of double straight line effect.

$$K = \frac{r_c^2 \ln(R_e/r_w)}{2L_e} \frac{1}{t} \ln \frac{y_0}{y_t}$$

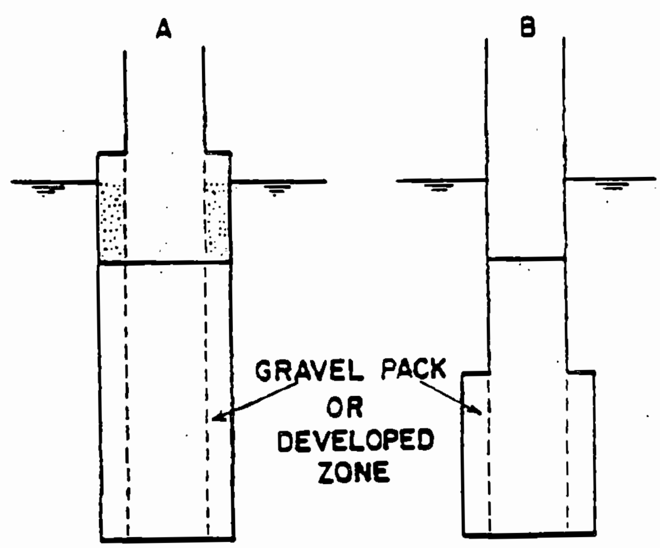


Fig. 5. Slug test for borehole with ground-water level below (A), and above (B) top of screen or perforated section.

REF: Bouwer (1989)

NUS CORPORATION AND SUBSIDIARIES — STANDARD CALCULATION SHEET

CLIENT: Allied Frankford	FILE NO.: 3814	BY: F. R. Morris	PAGE 1 OF 1
SUBJECT: Inputs for Aqtesolv		CHECKED BY:	DATE: 3/2/92

Slug Test Data — Bouwer-Rice Method

Slugt 1 : Rising Head Test

1. Initial drawdown (y) in well
2. Radius of well casing (should be R_c)
3. Radius of well (includes gravel pack) R_w

Slugt 2 :

1. Saturated Thickness (H)
2. Screen length
3. Static Height of water in well

tsdata : Time (min.) ↓   Drawdown (ft.) ↓   Weight (1) ↓

NUS CORPORATION AND SUBSIDIARIES			STANDARD CALCULATION SHEET
CLIENT: Allied Frankford	FILE NO.: 3814	BY: F. R. Morris	PAGE 1 OF 1
SUBJECT: Effective Radius of MWs @ Allied		CHECKED BY: WLaPARL	DATE: 3/2/92

(2" dia csg. 8" borehole gravel pack OD)

$$r_e = \left[\left(r_c^2 + n\left(r_w^2 - r_c^2\right)\right]^{1/2}$$

where:

r_e = Effective Radius of well

r_c = Radius of casing

r_w = Radius of Well (borehole containing GP)

n = Porosity of the gravel pack

$$r_e = \left[\left(r_c^2 + n\left(r_w^2 - r_c^2\right)\right]^{1/2}$$

$$r_e = \left[(.083)^2 + .30\left(.333^2 - .083^2\right)\right]^{1/2}$$

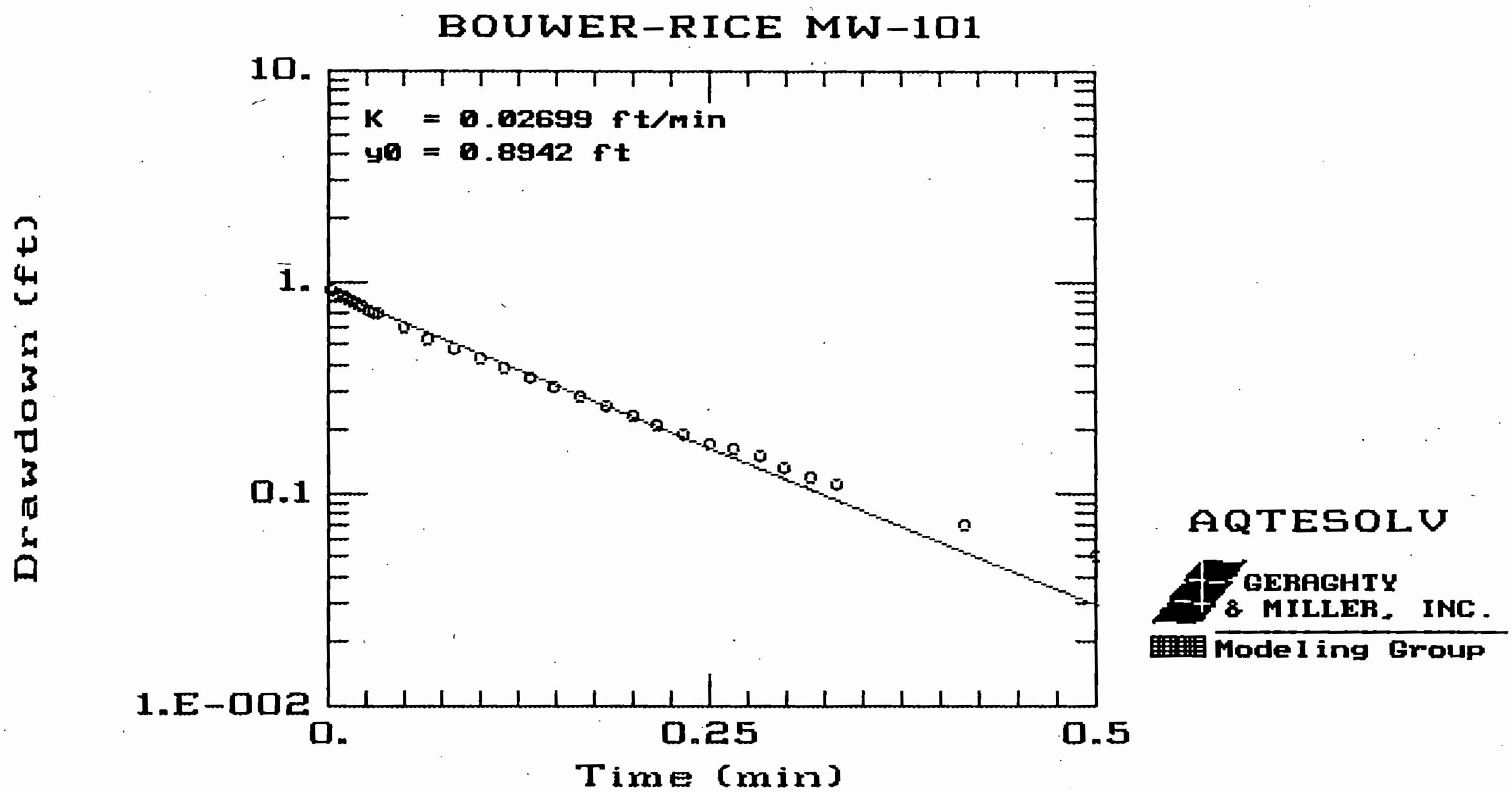
$$r_e = \left[(.007) + .30\,(.104)\right]^{1/2}$$

$$r_e = \left[.007 + .03\right]^{1/2}$$

$$r_e = \left[.038\right]^{1/2}$$

r_e = .195 feet

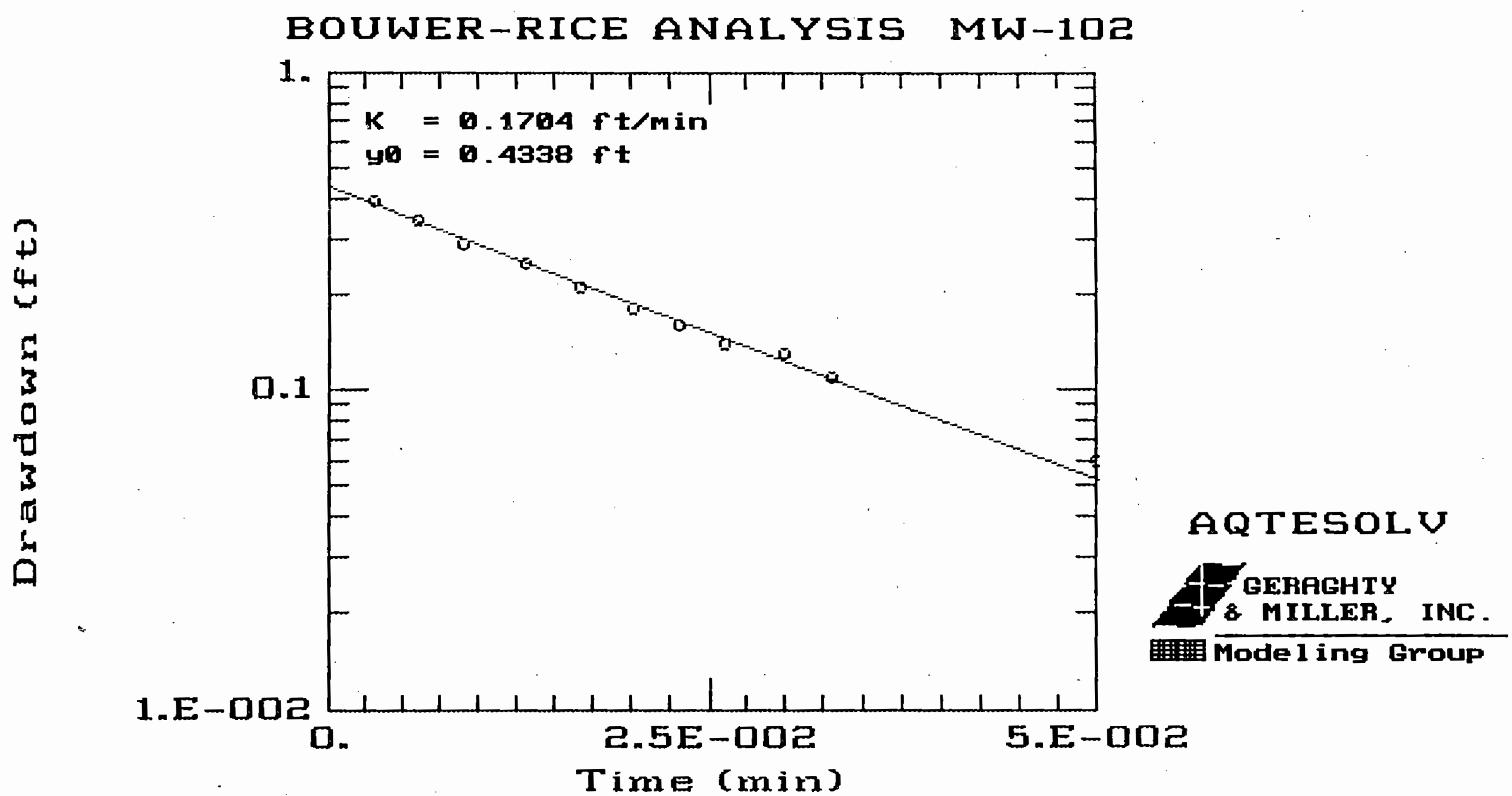
```
BOUWER-RICE MW-101
slugt1
0.96
0.195
0.333
slugt2
20
10
7.56
tsdata
0.003   0.92   1
0.007   0.88   1
0.01    0.85   1
0.013   0.82   1
0.017   0.8    1
0.02    0.78   1
0.023   0.76   1
0.027   0.73   1
0.03    0.71   1
0.033   0.7    1
0.05    0.61   1
0.067   0.54   1
0.083   0.48   1
0.1     0.43   1
0.117   0.39   1
0.133   0.35   1
0.15    0.32   1
0.167   0.29   1
0.183   0.26   1
0.2     0.23   1
0.217   0.21   1
0.233   0.19   1
0.25    0.17   1
0.267   0.16   1
0.283   0.15   1
0.3     0.13   1
0.317   0.12   1
0.333   0.11   1
0.417   0.07   1
0.5     0.05   1
0.583   0.04   1
0.667   0.02   1
0.75    0.01   1
0.833   0.01   1
0.917   0.01   1
1   0.01   1
```


BOUWER-RICE MW-101
K = 0.02699 ft/min
y0 = 0.8942 ft
10.
1.
0.1
1.E-002
Drawdown (ft)
0.
0.25
0.5
Time (min)
AQTESOLV
GERAGHTY & MILLER, INC.
Modeling Group

BOUWER-RICE ANALYSIS MW-102

slugt1
0.44
0.195
0.333
slugt2
20
10
8.28
tsdata

0.003	0.39	1
0.006	0.34	1
0.009	0.29	1
0.013	0.25	1
0.0166	0.21	1
0.02	0.18	1
0.023	0.16	1
0.026	0.14	1
0.03	0.13	1
0.033	0.11	1
0.05	0.06	1
0.066	0.04	1
0.083	0.01	1
0.1	0.01	1
0.12	0.01	1
0.13	0.01	1
0.15	0.01	1
0.17	0.01	1
0.183	0.01	1
0.2	0.01	1


BOUWER-RICE ANALYSIS MW-102
K = 0.1704 ft/min
y0 = 0.4338 ft
1.
0.1
1.E-002
0.
2.5E-002
5.E-002
Time (min)
Drawdown (ft)
AQTESOLV
GERAGHTY & MILLER, INC.
Modeling Group

BOUWER-RICE ANALYSIS MW-103

slugt1

1.49

0.195

0.333

slugt2

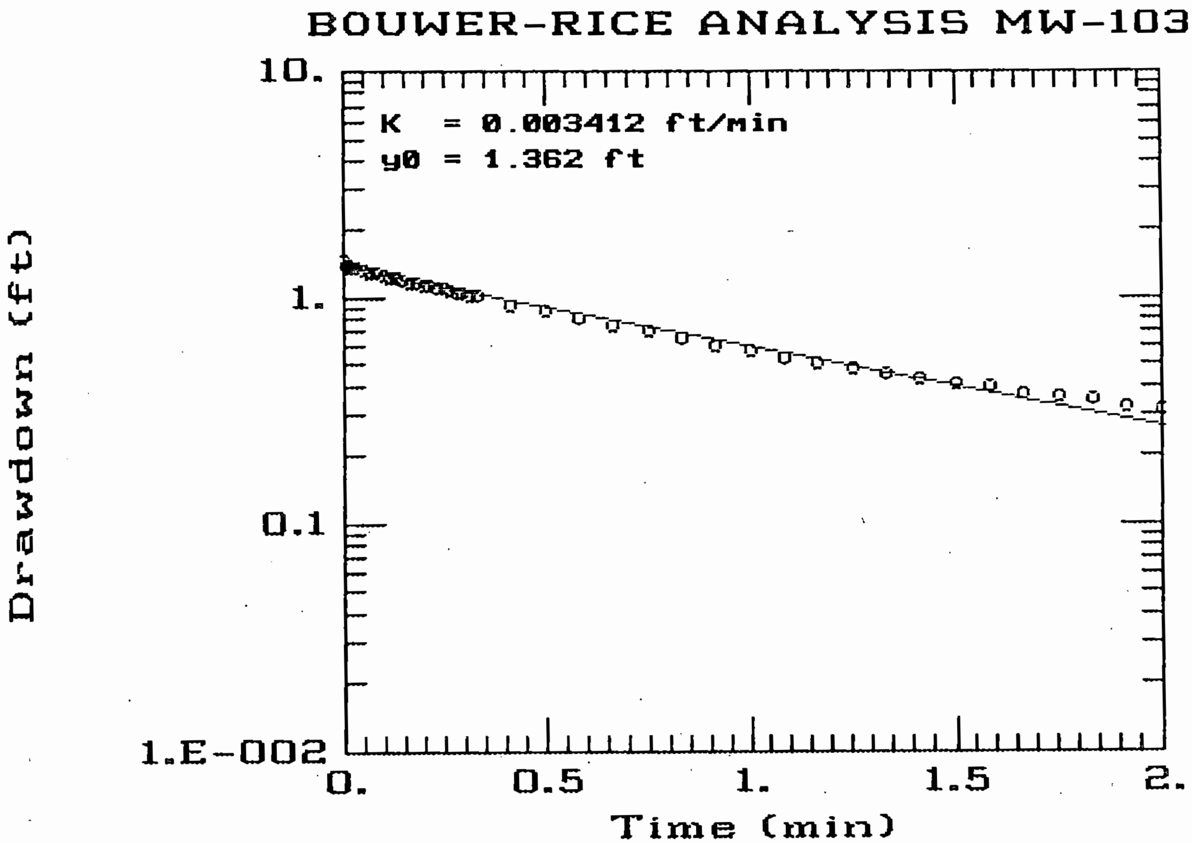
15

10

9.15

tsdata

0.003	1.47	1
0.007	1.4	1
0.01	1.39	1
0.013	1.38	1
0.017	1.37	1
0.02	1.37	1
0.023	1.36	1
0.027	1.35	1
0.03	1.34	1
0.033	1.34	1
0.05	1.31	1
0.067	1.29	1
0.083	1.28	1
0.1	1.26	1
0.117	1.23	1
0.133	1.22	1
0.15	1.2	1
0.167	1.17	1
0.183	1.16	1
0.2	1.14	1
0.217	1.12	1
0.233	1.1	1
0.25	1.09	1
0.267	1.07	1
0.283	1.05	1
0.3	1.04	1
0.317	1.02	1
0.333	1.01	1
0.417	0.93	1
0.5	0.87	1
0.583	0.81	1
0.667	0.75	1
0.75	0.7	1
0.833	0.65	1
0.917	0.61	1
1	0.57	1
1.083	0.54	1
1.167	0.51	1
1.25	0.48	1
1.333	0.46	1
1.417	0.43	1
1.5	0.41	1
1.583	0.4	1
1.667	0.37	1
1.75	0.36	1
1.833	0.35	1
1.917	0.33	1
2	0.32	1
2.5	0.25	1
3	0.21	1
3.5	0.17	1
4	0.15	1
4.5	0.13	1
5	0.13	1
5.5	0.11	1
6	0.1	1
6.5	0.1	1
7	0.09	1
7.5	0.09	1



AQTESOLV

GERAGHTY & MILLER, INC.

Modeling Group

HALLIBURTON NUS Environmental Corporation and Subsidiaries			STANDARD CALCULATION SHEET
CLIENT: ALLIED FRANKFORD	FILE NO.: 3814	BY: R. GOOD	PAGE 1 OF 1
SUBJECT: HYDRAULIC CONDUCTIVITY SUMMARY		CHECKED BY:	DATE: 3/9/92

HYDRAULIC CONDUCTIVITY, MW-101

0.02699 ft/min × 60 min/hr × 24 hr/day = 38.9 ft/day

0.02699 ft/min × 12 in/ft × 2.54 cm/in × 1 min/60 sec = 1.37×10^{-2} cm/sec

HYDRAULIC CONDUCTIVITY, MW-102

0.1704 ft/min × 60 min/hr × 24 hr/day = 245.4 ft/day

0.1704 ft/min × 12 in/ft × 2.54 cm/in × 1 min/60 sec = 8.66×10^{-2} cm/sec

HYDRAULIC CONDUCTIVITY, MW-103

0.003412 ft/min × 60 min/hr × 24 hr/day = 4.91 ft/day

0.003412 ft/min × 12 in/ft × 2.54 cm/in × 1 min/60 sec = 1.73×10^{-3} cm/sec

APPENDIX E
LIGHT NON-AQUEOUS PHASE LIQUID (LNAPL) CALCULATIONS

HALLIBURTON NUS Environmental Corporation and Subsidiaries			STANDARD CALCULATION SHEET
CLIENT: ALLIED FRANKFORD	FILE NO.: 3814	BY: R. GOOD	PAGE 1 OF 3
SUBJECT: LNAPL VOLUME CALCULATIONS		CHECKED BY: J. TREPANOWSKI	DATE: 4/22/97

MAXIMUM LNAPL VOLUME – VAN GENUCHTEN MODEL (LENHARD & PARKER, 1990)

LNAPL LAYER AREAS (FIGURE 4-1) CALCULATED FROM PLANIMETER MEASUREMENTS

AREA WITHIN 0-INCH CONTOUR, $A_0 = 724{,}908\ ft^2 = 16.64$ Acres

AREA WITHIN 12-INCH CONTOUR, $A_{12} = 376{,}834\ ft^2 = 8.65$ Acres

AREA WITHIN 24-INCH CONTOUR, $A_{24} = 118{,}662\ ft^2 = 2.72$ Acres

LNAPL AREA 1, BETWEEN 0 AND 12 INCH CONTOURS, $A_1 = A_0 - A_{12}$

$= 724{,}908\ ft^2 - 376{,}834\ ft^2$

$= 348{,}074\ ft^2$

LNAPL AREA 2, BETWEEN 12 AND 24 INCH CONTOURS, $A_2 = A_{12} - A_{24}$

$= 376{,}834\ ft^2 - 118{,}662\ ft^2$

$= 258{,}172\ ft^2$

LNAPL AREA 3, WITHIN 24 INCH CONTOUR, $A_3 = A_{24}$

$= 118{,}662\ ft^2$

AVG. THICKNESS, LNAPL AREA 1 (0–12 INCHES), $T_1 = 0.5$ ft.

AVG. THICKNESS, LNAPL AREA 2 (12–24 INCHES), $T_2 = 1.5$ ft.

AVG. THICKNESS, LNAPL AREA 3 (24–30 INCHES), $T_3 = 2.25$ ft.

LNAPL VOLUME WITHIN AREA N, $V_N = A_N \times T_N \times \phi$, WHERE

ϕ = POROSITY SATURATED WITH LNAPL.

TOTAL LNAPL VOLUME WITHIN LAYER, $V_T = \sum V_N = V_1 + V_2 + V_3$

$= \phi \times [(A_1 \times T_1) + (A_2 \times T_2) + (A_3 \times T_3)]$

$= \phi \times [(348{,}074\ ft^2 \times 0.5\ ft) + (258{,}172\ ft^2 \times 1.5\ ft) + (118{,}662\ ft^2 \times 2.25\ ft)]$

$= \phi \times [174{,}037\ ft^3 + 387{,}258\ ft^3 + 266{,}990\ ft^3]$

$= \phi \times 828{,}285\ ft^3$

$\phi_{(max)} = S_{max} \times \phi_T$ WHERE S_{max} = MAXIMUM LNAPL SATURATION FROM FIG. 4 OF LENHARD & PARKER, 1990 AT MAX. LAYER THICKNESS, $T_{max} = 30$ IN. (~76 cm)

$S_{max} = 30\% = 0.30$; ϕ_T = TOTAL SEDIMENT POROSITY $= 35\% = 0.35$

$\phi_{max} = 0.3 \times 0.35 = 0.105$

MAXIMUM LNAPL VOLUME, $V_{T(max)} = \phi_{max} \times 828{,}285 = 86970\ ft^3$

$(\times 7.48052\ gal/ft^3) = 650{,}581$ gal.

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ESTIMATED LNAPL VOLUME, VAN GENUCHTEN MODEL

EXAMPLE SOIL TYPE 1 (FIGURE 4 OF LENHARD & PARKER, 1990)

LNAPL AREA 1, LNAPL SATURATION FOR LAYER THICKNESS $T_1 = 0.5$ ft (~ 15 cm)

$S_1 = 10\% = 0.10$

LNAPL AREA 1, LNAPL SATURATED POROSITY; $\phi_1 = S_1 \times \phi_T$, WHERE

ϕ_T = TOTAL POROSITY OF 35% = 0.35

$\phi_1 = 0.10 \times 0.35 = 0.035$

LNAPL AREA 2, LNAPL SATURATION FOR LAYER THICKNESS $T_2 = 1.5$ ft (~ 46 cm)

$S_2 = 23\% = 0.23$

LNAPL AREA 2, LNAPL SATURATED POROSITY, $\phi_2 = S_2 \times \phi_T$

$\phi_2 = 0.23 \times 0.35 = 0.0805$

LNAPL AREA 3, LNAPL SATURATION FOR LAYER THICKNESS $T_3 = 2.25$ ft (~ 69 cm)

$S_3 = 27\% = 0.27$

LNAPL AREA 3, LNAPL SATURATED POROSITY, $\phi_3 = S_3 \times \phi_T$

$\phi_3 = 0.27 \times 0.35 = 0.0945$

TOTAL LNAPL VOLUME, SOIL TYPE 1

$V_T = V_1 + V_2 + V_3$

$= (\phi_1 \times A_1 \times T_1) + (\phi_2 \times A_2 \times T_2) + (\phi_3 \times A_3 \times T_3)$

$= (0.035 \times 348{,}074\ ft^2 \times 0.5\ ft) + (0.0805 \times 258{,}172\ ft^2 \times 1.5\ ft) +$
$(0.0945 \times 118{,}662\ ft^2 \times 2.25\ ft)$

$= 6091\ ft^3 + 31{,}174\ ft^3 + 25{,}231\ ft^3$

$= 62{,}496\ ft^3$ $(\times 7.48052\ gal/ft^3)$

$= 467{,}503$ gal

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ESTIMATED LNAPL VOLUME, VAN GENUCHTEN MODEL

EXAMPLE SOIL TYPE 2 (FIGURE 4 OF LENHARD & PARKER, 1990)

LNAPL AREA 1, LNAPL SATURATION FOR LAYER THICKNESS $T_1 = 0.5$ ft (~ 15 cm)

$S_1 = 1\% = 0.01$

LNAPL AREA 1, LNAPL SATURATED POROSITY $\phi_1 = S_1 \times \phi_T$

$\phi_1 = 0.01 \times 0.35 = 0.0035$

LNAPL AREA 2, LNAPL SATURATION FOR LAYER THICKNESS $T_2 = 1.5$ ft (~ 46 cm)

$S_2 = 7\% = 0.07$

LNAPL AREA 2, LNAPL SATURATED POROSITY $\phi_2 = S_2 \times \phi_T$

$\phi_2 = 0.07 \times 0.35 = 0.0245$

LNAPL AREA 3, LNAPL SATURATION FOR LAYER THICKNESS $T_3 = 2.25$ ft (~ 69 cm)

$S_3 = 16\% = 0.16$

LNAPL AREA 3, LNAPL SATURATED POROSITY $\phi_3 = S_3 \times \phi_T$

$\phi_3 = 0.16 \times 0.35 = 0.056$

TOTAL LNAPL VOLUME, SOIL TYPE 2

$V_T = V_1 + V_2 + V_3$

$= (\phi_1 \times A_1 \times T_1) + (\phi_2 \times A_2 \times T_2) + (\phi_3 \times A_3 \times T_3)$

$= (0.0035 \times 348{,}074\ ft^2 \times 0.5\ ft) + (0.0245 \times 258{,}172\ ft^2 \times 1.5\ ft)$

$+ (0.056 \times 118{,}662\ ft^2 \times 2.25\ ft)$

$= 609\ ft^3 + 9488\ ft^3 + 14951\ ft^3$

$= 25{,}048\ ft^3$ ($\times$ 7.48052 gal/ft^3)

$= 187{,}372$ gal

Estimation of Free Hydrocarbon Volume from Fluid Levels in Monitoring Wells

by R. J. Lenhard and J. C. Parker[a]

ABSTRACT

Under the assumption of local vertical equilibrium, fluid pressure distributions specified from well fluid levels in monitoring wells may be used to predict water and hydrocarbon saturation profiles given expressions for air-water-hydrocarbon saturation-pressure relations. Vertical integration of the oil-saturation profile yields the actual oil volume in porous media per unit area adjacent to the well. Three-phase fluid distributions are predicted using a scaling procedure which requires knowledge of two-phase air-water saturation-pressure relations, hydrocarbon density, and hydrocarbon surface tension. Air-water saturation-pressure relations are parameterized by either the Brooks-Corey or van Genuchten expressions. Parameters in the models are estimated from grain-size distribution data for two hypothetical soils.

Results reveal that whereas the distance above an oil-water table at which oil saturations become zero may be independent of soil type, estimated light nonaqueous phase liquid (LNAPL) volumes per unit area may differ substantially. Hence, estimates of LNAPL volume cannot be inferred directly from soil LNAPL thickness or well LNAPL thickness data without consideration of effects of soil properties. Furthermore, it is demonstrated that no simple linear conversion scheme can be employed to relate the height of LNAPL in a monitoring well to the LNAPL volume in porous media. Effects of grain-size distribution and well LNAPL thickness on the ratio of actual LNAPL thickness in the aquifer to well LNAPL thickness are shown.

INTRODUCTION

Surface spills of hydrocarbons and leakage from underground storage tanks are a widespread source of ground-water contamination. Low-density nonaqueous phase liquids (LNAPL) may accumulate above the water-saturated zone and serve as a source of soluble and volatile constituents that can be transported from the contaminated area in the aqueous and gaseous phases, respectively. The distribution of LNAPL in the subsurface will be a function of LNAPL, water and air pressures, and the pore-size distribution of the porous medium.

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At equilibrium, abrupt changes in fluid contents with elevation do not generally occur except in porous media with very uniform pore-size distributions or in layered porous media with contrasting pore-size distributions. Thus, oil-saturated "pancakes" do not develop in the vast majority of soils and aquifers. Immediately above the water-saturated zone, the soil will contain variable saturations of LNAPL and water. Unfortunately, the use of uniform grain-size materials in many published laboratory air-oil-water flow experiments has contributed to the misconception about the development of an "oil pancake."

To assess the volume of a spill and to design and monitor recovery operations, observation wells are commonly installed in which LNAPL thickness is measured. Interpretation of LNAPL thickness data from observation wells, however, presents a number of difficulties. It is well-known that actual hydrocarbon volume per unit surface area ("hydrocarbon specific volume") is less than the LNAPL thickness in a well (van Dam, 1967). de Pastrovich *et al.* (1979) proposed that the measured LNAPL thickness in monitoring wells ("well product thickness") is approximately four times the thickness of the soil zone in which free hydrocarbon is observable ("soil hydrocarbon thickness"). They obtained this ratio via a very simplistic force balance subject to a number of simplifying assumptions.

Hall *et al.* (1984) investigated the relationship between oil thickness in porous media to the thickness of oil in an observation well by adding oil incrementally to sandy porous media packed in large laboratory scale boxes. Coarse-, medium-, and fine-textured sands were employed. The water pressure distribution in the sands prior to oil addition corresponded to main drainage air-water saturation-capillary pressure relations. After addition of a critical oil volume which increased as soil grain size diminished, a 1:1 relationship between soil hydrocarbon thickness and well hydrocarbon thickness was observed. Their observations did not agree with the relationship developed by de Pastrovich *et al.* (1979). Consequently, Hall *et al.* (1984) proposed that hydrocarbon thickness in soils be estimated from well hydrocarbon thickness after applying a porous media dependent correction factor. They did not, however, propose a technique to evaluate the correction factor from basic soil properties.

In another laboratory investigation of the relationship between soil and well hydrocarbon thickness, Hampton and Miller (1988) found the relationships proposed by de Pastrovich *et al.* (1979) and Hall *et al.* (1984) to be inadequate for describing their experimental observations. Hampton and Miller further questioned the relevance of estimating soil hydrocarbon thickness since it does not translate directly to hydrocarbon specific volume which is the quantity of more fundamental interest.

To estimate hydrocarbon specific volume, water and hydrocarbon saturation distributions in the soil must be known. For an air-hydrocarbon-water fluid system in water-wet porous media, water saturation depends on the capillary pressure between water and hydrocarbon phases, and total liquid saturation depends on the capillary pressure between hydrocarbon and gas phases. Fluid saturation distributions, therefore, will be controlled by saturation-capillary pressure relations of the soil which in turn depend on the pore-size distribution. If fluid pressure distributions can be inferred from well fluid levels, and three-phase saturation-capillary pressure relations for the soil are known, fluid saturation distributions can be predicted and integrated to determine the corresponding hydrocarbon specific volume.

Our purpose in this paper is to present a physically based methodology for estimating vertical hydrocarbon distribution and hydrocarbon specific volume from observation well fluid levels. Procedures for practical implementation of the methodology will be presented and results will be given to demonstrate effects of grain-size distribution and well LNAPL thickness on the ratio of hydrocarbon specific volume to well LNAPL thickness.

VERTICAL EQUILIBRIUM PRESSURE DISTRIBUTION

We consider the situation in which liquid velocities in the vertical direction may be assumed small relative to those in the horizontal. More specifically, we assume that vertical pressure distributions approximate hydrostatic conditions and that local equilibrium exists within fluids in the well and adjacent porous media. The vertical equilibrium assumption may be exactly stated as

$$\partial \psi_w / \partial z = 0 \qquad (1a)$$

$$\partial \psi_o / \partial z = 0 \qquad (1b)$$

where z is elevation, and ψ_w and ψ_o are piezometric heads of water and oil defined by

$$\psi_w = h_w + z \qquad (2a)$$

$$\psi_o = h_o + \rho_{ro}\, z \qquad (2b)$$

where ρ_{ro} is the oil specific gravity (ratio of oil to water density), and h_w and h_o are water height-equivalent pressure heads of water and oil phases given by

$$h_w = P_w / g\rho_w \qquad (3a)$$

$$h_o = P_o / g\rho_w \qquad (3b)$$

where P_w and P_o are water and oil phase pressures, g is gravitational acceleration, and ρ_w is the reference density of water. (See Appendix for summary of notation.)

To relate the vertical pressure distributions to well fluid levels, we introduce the concept of fluid "table" elevations. Consider a system containing air, water, and LNAPL in which a screened well and a piezometer are installed (Figure 1). An oil lens is observed in the screened well which can be characterized by the air-oil table elevation, z_{ao}, at which the gauge oil pressure is zero, and the oil-water table elevation, z_{ow}, at which elevation water and oil pressures are equal. From the piezometer tube which extends below the oil-water interface we may also define an air-water table elevation, z_{aw}, where the gauge water pressure is zero. Employing these fluid table elevation definitions, integration of (1) and (2) yields

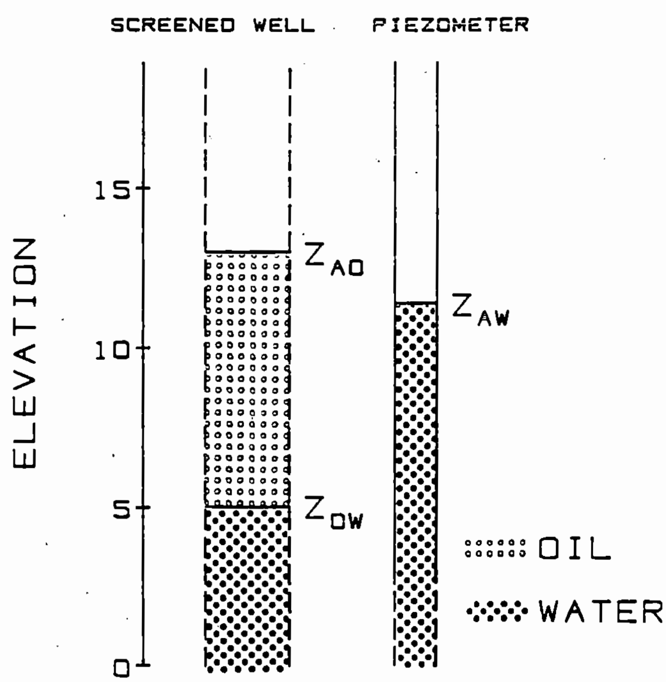

Fig. 1. Definition of fluid levels in monitoring wells.

$$h_w = z_{aw} - z \tag{4a}$$

$$h_o = \rho_{ro}(z_{ao} - z) \tag{4b}$$

which upon manipulation yields an expression relating the various table elevations by

$$z_{aw} = (1 - \rho_{ro}) z_{ow} + \rho_{ro} z_{ao} \tag{5}$$

From (4) and (5), it can be seen that stipulation of any two of the three fluid table elevations completely defines air-oil-water static vertical head distributions; hence, installation of a piezometer tube is not required.

Since fluid saturations will depend directly on pressure differences between phases as will be discussed in detail in the following section, it is desirable to introduce capillary heads defined by

$$h_{ao} = h_a - h_o \tag{6a}$$

$$h_{ow} = h_o - h_w \tag{6b}$$

where h_w and h_o are as previously defined, and h_a is the gas phase head which we assume to be zero (i.e., atmospheric pressure). From (4)-(6), expressions for h_{ao} and h_{ow} as functions of elevation may be obtained via

$$h_{ao} = \rho_{ro}(z - z_{ao}) \tag{7a}$$

$$h_{ow} = (1 - \rho_{ro})(z - z_{ow}) \tag{7b}$$

which indicates that the ij-phase capillary head depends only on the elevation relative to the ij-phase table (i,j = a,o,w).

THREE-PHASE SATURATION-PRESSURE RELATIONS

Parametric Representation

To describe vertical fluid saturation distributions, relationships between fluid pressures (P) and saturations (S) must be known. We obtain these by assuming after Leverett (1941) and Corey *et al.* (1956) that water and total liquid saturations in a water-wet air-oil-water system will be independent functions of oil-water and air-oil capillary heads, respectively, and furthermore that the functions may be scaled by relations of the form proposed by Parker *et al.* (1987)

$$\bar{S}_w(\beta_{ow} h_{ow}) = S^*(h^*) \tag{8a}$$

$$\bar{S}_t(\beta_{ao} h_{ao}) = S^*(h^*) \tag{8b}$$

where β_{ow} and β_{ao} are fluid-pair dependent scaling factors, and effective water and total liquid saturations are defined, respectively, by

$$\bar{S}_w = \frac{S_w - S_m}{1 - S_m} \tag{9a}$$

$$\bar{S}_t = \frac{S_w + S_o - S_m}{1 - S_m} \tag{9b}$$

in which S_w and S_o are actual water and oil saturations, and S_m is a minimum or "irreducible" wetting phase saturation. Taking the reference for scaling as the uncontaminated two-phase air-water system, the scaled function $S^*(h^*)$ is given by

$$S^*(h^*) = \bar{S}_w^{prist}(h_{aw}) \tag{10}$$

where $\bar{S}_w^{prist}$ denotes the effective saturation of water in a pristine air-water system, and $h_{aw} = h_a - h_w$ is the air-water capillary head.

The scaling coefficients β_{ao} and β_{ow} in (8) may be estimated from air-oil and oil-water interfacial tension data (Lenhard and Parker, 1987) as

$$\beta_{ao} = \sigma_{aw}/\sigma_{ao} \tag{11a}$$

$$\beta_{ow} = \sigma_{aw}/\sigma_{ow} \tag{11b}$$

where σ_{aw} is the surface tension of uncontaminated water; σ_{ao} is the surface tension of the hydrocarbon; and σ_{ow} is the interfacial tension between water and hydrocarbon. In the event that soluble hydrocarbon components have a negligible effect on the surface tension of water, then $\sigma_{ao} + \sigma_{ow} = \sigma_{aw}$ implying

$$1/\beta_{ao} + 1/\beta_{ow} = 1 \tag{12}$$

Reasonable estimates of β_{ao} and β_{ow} for gasolines obtained from interfacial tension data (Weiss, 1980) are 3.2 ± 0.2 and 1.45 ± 0.05, respectively. Note that these values are consistent with (12).

Given a suitable expression for $S^*(h^*)$, employing (7) in (8) enables determination of vertical saturation distributions. In previous studies (Lenhard and Parker, 1988; Lenhard *et al.*, 1988a) we have found that the parametric model of van Genuchten (1980) provides an accurate description of two- and three-phase S-P relations. The function has the form

$$S^*(h^*) = [1 + (\alpha h^*)^n]^{-m} \qquad h^* > 0 \tag{13a}$$

$$S^*(h^*) = 1 \qquad h^* \leqslant 0 \tag{13b}$$

where α, n, and $m = 1 - 1/n$ are van Genuchten (VG) model parameters. An alternative model that has been used widely to describe S-P relations is that of Brooks and Corey (1966) which has the scaled form

$$S^*(h^*) = (h_d/h^*)^\lambda \qquad h^* > h_d \tag{14a}$$

$$S^*(h^*) = 1 \qquad h^* \leqslant h_d \tag{14b}$$

where h_d and λ are Brooks-Corey (BC) model parameters.

Estimation of Equilibrium Retention Parameters

A variety of methods may be employed to measure equilibrium water retention behavior in the laboratory. The procedures are, however, rather time-consuming and unfamiliar to many commercial laboratories. A simple alternative approach to model calibration which may be adopted with some concomitant loss of accuracy involves estimation of hydraulic properties from readily available grain-size distribution data. Mishra *et al.* (1988) proposed a method based on a modified form of the Arya and Paris (1981) model to convert grain-size distribution data to an equivalent soil-water retention function which is then fitted to the VG model. To demonstrate effects of grain-size distribution on hydrocarbon distributions and hydrocarbon specific volume, we employ the method of Mishra *et al.* (1988) to determine VG parameters for two hypothetical soils with grain-size distributions illustrated in Figure 2. Both soils have median grain diameters of 0.2 mm with Soil 1 exhibiting a narrow grain-size distribution and Soil 2 a broader distribution. Whereas the soils have identical media grain diameters, the mean grain diameter for Soil 1 is 0.33 mm and that for Soil 2 is 1.48 mm.

Equilibrium VG retention parameters were computed with the interactive program SOILPROP (information concerning SOILPROP is available upon request) described by Mishra *et al.* (1988). From input grain-size distribution data, SOILPROP delineates 100 particle-size classes and assigns a pore volume, volumetric water content (i.e., volume of water/volume of soil) and representative pore radius to each class. From the pore radii, corresponding capillary heads are computed. The resulting volumetric water content-capillary head data are fit to (13) by nonlinear least-squares

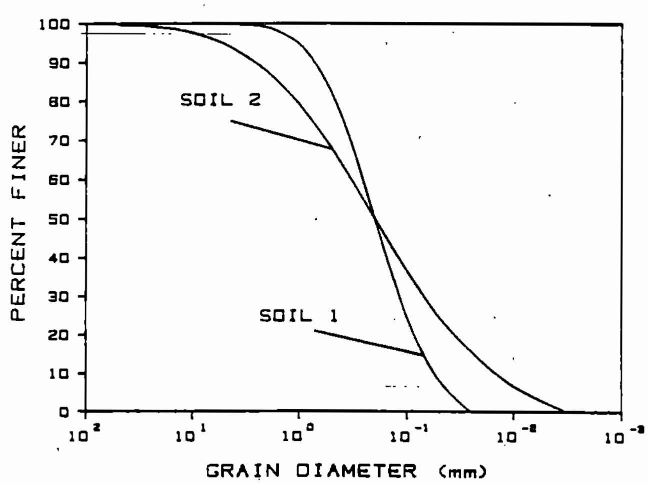

Fig. 2. Particle-size distributions of the hypothetical soils.

Table 1. van Genuchten and Brooks-Corey Model Parameters and Fluid Properties

	van Genuchten			Brooks-Corey		
	α	n	S_m	h_d	λ	S_m
Equilibrium Model Parameters:						
Soil 1	0.025	2.297	0.0	25.22	0.917	0.0
Soil 2	0.126	1.281	0.0	6.35	0.269	0.0
Quasi-Static Model Parameters:						
Soil 1	0.027	2.434	0.13	23.58	0.992	0.13
Soil 2	0.185	1.645	0.58	3.45	0.535	0.58
Porosity, ϕ					0.43	
Density ratio, ρ_{ro}					0.73	
Oil-water scaling factor, β_{ow}					1.45	
Air-oil scaling factor, β_{ao}					3.20	

regression to estimate the VG parameters α and n and irreducible water saturation, S_m. Soil porosity was assumed to be 0.43 for both soils. Calculated equilibrium VG parameters for the soils are given in Table 1.

To convert VG parameters to "equivalent" BC model parameters, SOILPROP employs the procedure of Lenhard *et al.* (1988b). The BC parameter λ is determined by equating the differential fluid saturation capacities, $\partial S/\partial h$, of the VG and BC models at an effective wetting fluid saturation of 0.5 which yields

$$\lambda = \frac{m}{1 - m}\left(1 - 0.5^{1/m}\right) \tag{15}$$

The BC parameter h_d is calculated by equating the functions at a match-point effective wetting fluid saturation as

$$h_d = \alpha^{-1}\, \bar{S}_x^{1/\lambda}\left(\bar{S}_x^{-1/m} - 1\right)^{1-m} \tag{16}$$

where $\bar{S}_x$ is the match-point effective saturation given by

$$\bar{S}_x = 0.72 - 0.35e^{-n^4} \tag{17}$$

Equilibrium BC parameters corresponding to the VG parameters computed in this fashion are listed in Table 1 for both soils.

Consideration of Vertical Nonequilibrium Effects

Since true equilibrium conditions do not generally occur in the field, fluid saturations may differ from those predicted for ideal hydrostatic conditions. As a first-order correction, we consider effects of nonequilibrium water distributions associated with gravity drainage conditions due to redistribution of intermittent water additions at the soil surface. It is well-known that under such conditions, water within the wetted zone drains rather quickly to a water content below which hydraulic conductivity is sufficiently small that vertical fluid redistribution virtually ceases although true equilibrium conditions have not been reached. This water content is commonly referred to as "field capacity." We refer to the resulting fluid distribution above a fixed water table as "quasi-static." To investigate the nature of the quasi-static distribution, transient vertical flow simulations were carried out for 200-cm-long soil columns initially near saturation and allowed to drain to a water table at the lower boundary with zero water flux at the upper surface. Equilibrium van Genuchten retention function parameters for the two soils were employed and the saturated hydraulic conductivity, K_s, of both soils was taken to be 170 cm d^{-1} as predicted by SOILPROP. After a period of six days, drainage rates had reached low values with fluid saturations changing less than 0.01 cm^3 cm^{-2} d^{-1} which was deemed a suitable point to define "field capacity." Simulated water saturation distributions for the two soils at six days are shown in Figure 3 as solid symbols.

A simple means of representing the quasi-static water content distribution is to employ a hydrostatic pressure distribution and correct for deviations by means of a fictitious saturation-capillary pressure relationship. To evaluate this quasi-static distribution, S_m', corresponds to the saturation at which hydraulic conductivity, K, approaches some specified small value. We choose the latter value to be 0.05 cm d^{-1} and compute the corresponding water saturation by inversion of the VG conductivity function

$$K = K_s \bar{S}_w^{1/2} [1 - (1 - \bar{S}_w^{1/m})^m]^2 \qquad (18)$$

Assuming true equilibrium conditions still occur near the water table, we refit VG model parameters to a subset of the equilibrium retention function for corrected effective saturations, $\bar{S}_w' = (S_w - S_m')/(1 - S_m')$, exceeding 0.5. The resulting quasi-static VG retention function parameters obtained in this fashion using an option in SOILPROP are given in Table 1 along with equivalent BC parameters obtained as described previously. Vertical saturation distributions predicted by the quasi-static VG parameters for equilibrium head distributions show reasonable correspondence with saturation profiles obtained in the dynamic simulations while true equilibrium parameters significantly underestimate water saturation (Figure 3). Accordingly, we will subsequently utilize quasi-static parameters as an expedient means of accommodating effects of vertical nonequilibrium in predicting three-phase fluid distributions.

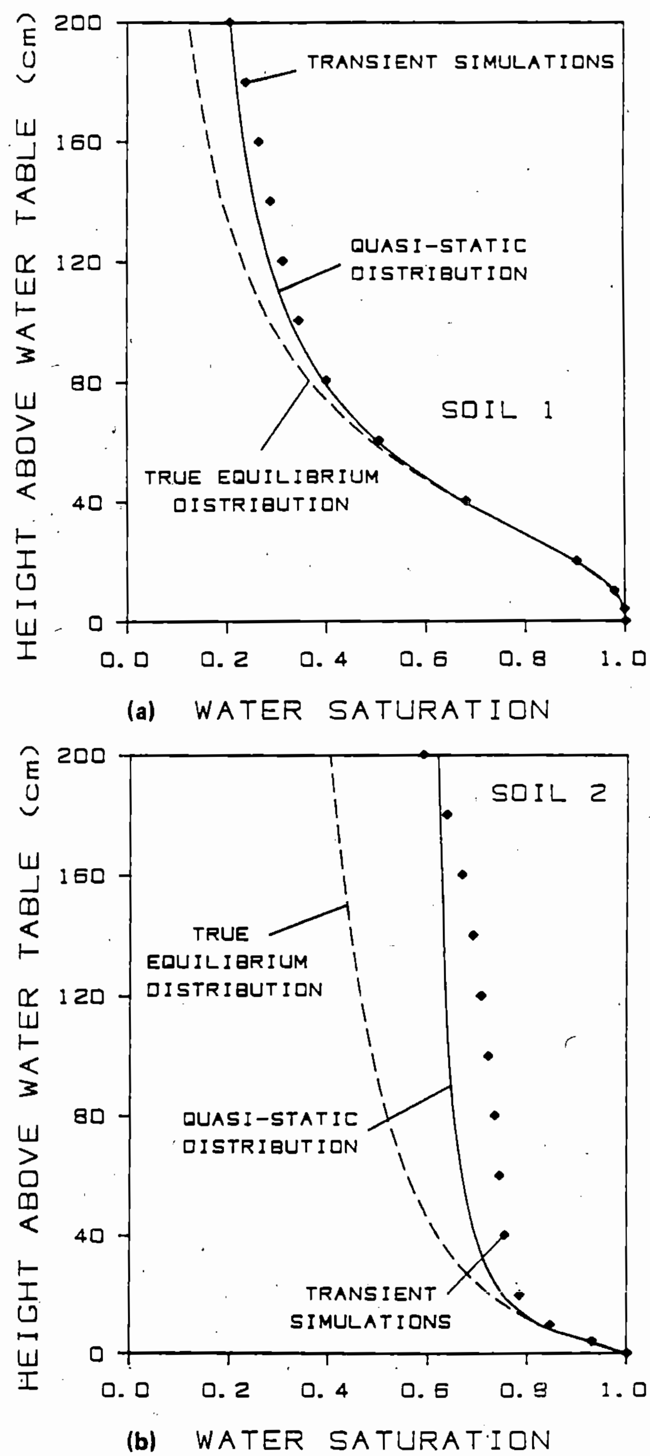

Fig. 3. Comparison of water distributions predicted by quasi-static (solid lines) and true equilibrium (broken lines) van Genuchten retention parameters to those obtained from numerical simulations (solid symbols) of a draining soil profile for (a) Soil 1, and (b) Soil 2.

VERTICAL FLUID SATURATION DISTRIBUTIONS

Vertical distributions of water and total liquid saturations were computed for both soil materials assuming depths to oil and water in an observation well of 1 and 2 m, respectively, using the van Genuchten and Brooks-Corey models. Fluid properties typical of gasoline were assumed (Table

1). Fluid distributions corresponding to quasi-static parameters are shown in Figure 4. Different fluid distributions are predicted for the two soils with more oil at lower elevations for the soil with the wider grain-size distribution (i.e., Soil 2). Correspondence between the VG and BC models is generally favorable for both soils except at low elevations especially for Soil 1 which has a higher air entry capillary head, h_d.

Soil hydrocarbon thickness, D_o, can be calculated from (7) and (8) as the depth over which $S_o > 0$ which leads to

$$D_o = \frac{\rho_{ro}\,\beta_{ao}\,H_o}{\beta_{ao}\,\rho_{ro} - \beta_{ow}(1 - \rho_{ro})} \tag{19}$$

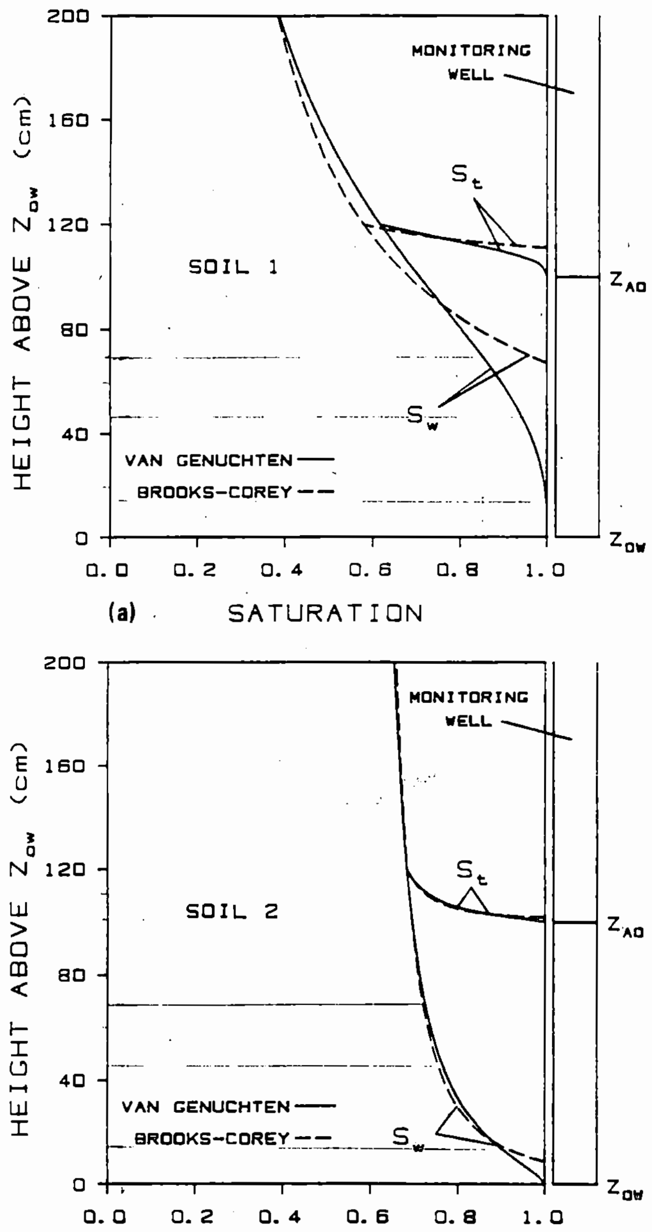

Fig. 4. Predicted water and total liquid distributions using van Genuchten and Brooks-Corey models assuming quasi-static conditions for (a) Soil 1 and (b) Soil 2.

where $H_o = z_{ao} - z_{ow}$ is the well hydrocarbon thickness. Note that input parameters required for (19) are oil and water densities, air-water, air-oil and oil-water interfacial tensions, and observed air-oil and oil-water fluid levels in the monitoring well. These quantities can either be measured directly in the field or can be determined readily in the laboratory with a high degree of accuracy and precision. Equation (19) is strictly valid only for the VG model which has finite S_o as $z \rightarrow z_{ow}$ from above. For the BC model, a well-defined oil-water capillary fringe (discussed in detail later) is predicted which may be subtracted from the right-hand side of (19). Using the parameters listed in Table 1 and a well hydrocarbon thickness, H_o, of 100 cm gives D_o = 120 cm. This thickness would be reduced by the oil-water capillary fringe thickness of approximately 65 cm for Soil 1 and 16 cm for Soil 2 for the BC model. Since S_o is quite variable over the oil-bearing zone and differs for the two soils (Figure 4), it is apparent that D_o provides no direct information concerning LNAPL volume in the soil.

RELATION BETWEEN WELL HYDROCARBON THICKNESS AND SPECIFIC VOLUME

Basic Relationships

The LNAPL volume in the soil per unit area in the horizontal plane (hydrocarbon specific volume) is given by

$$V_o = \int_{z_{ow}}^{z_u} \phi\, S_o\, dz \tag{20}$$

where z_u is the elevation of the soil surface, z_{ow} is the oil-water table elevation, below which free oil cannot occur under the assumed vertical equilibrium conditions, and ϕ is the porosity of the soil.

For the VG model, employing (7), (8), and (13) to define $S_o(z)$ leads to an integral expression for V_o which cannot be solved in closed form. Here, we employ a simple numerical quadrature scheme to evaluate V_o for the VG model. For the BC model, it is convenient to recast (20) in the form

$$V_o = \phi \int_{z_{fow}}^{\Gamma} [1 - S_w(z)]\, dz + \phi \int_{\Gamma}^{z_u} S_t(z)\, dz - \phi \int_{\Gamma}^{z_u} S_w(z)\, dz \tag{21}$$

where z_{fow} is the elevation below which complete water saturation occurs (upper boundary of oil-water capillary fringe), and Γ is the minimum of z_{fow} or z_u where z_{fao} is the elevation below which complete liquid saturation occurs (upper boundary of air-oil capillary fringe). The functional relationships between fluid saturations and elevations, $S_w(z)$ and $S_t(z)$, can be determined via (7) and (8).

For the BC model, the elevations of the water-saturated zone or upper boundary of the oil-water capillary fringe, z_{fow}, and total liquid-saturated zone or upper boundary of the air-oil capillary fringe, z_{fao}, are given by

$$z_{fow} = z_{ow} + \frac{h_d}{(1 - \rho_{ro})\beta_{ow}} \tag{22a}$$

$$z_{fao} = z_{ao} + \frac{h_d}{\rho_{ro}\beta_{ao}} \tag{22b}$$

Integration of (21) using the BC model for $S_w(z)$ and $S_t(z)$ for $z_{fao} > z_u$ yields

$$V_o = \frac{\phi(1 - S_m)}{1 - \rho_{ro}}(A - B) - \frac{\phi(1 - S_m)}{(1 - \rho_{ro})(1 - \lambda)} \cdot B^{\lambda}(A^{1-\lambda} - B^{1-\lambda}) \tag{23a}$$

and for $z_{fao} \leqslant z_u$, we obtain

$$V_o = \frac{\phi(1 - S_m)}{1 - \rho_{ro}}(C - B) - \frac{\phi(1 - S_m)}{(1 - \rho_{ro})(1 - \lambda)} \cdot B^{\lambda}(C^{1-\lambda} - B^{1-\lambda}) + \frac{\phi S_m}{\rho_{ro}}(D - E) + \frac{\phi(1 - S_m)}{\rho_{ro}(1 - \lambda)} \cdot E^{\lambda}(D^{1-\lambda} - E^{1-\lambda}) - \frac{\phi S_m}{1 - \rho_{ro}}(A - C) - \frac{\phi(1 - S_m)}{(1 - \lambda)(1 - \rho_{ro})} B^{\lambda}(A^{1-\lambda} - C^{1-\lambda}) \tag{23b}$$

where $A = (1 - \rho_{ro})(z_u - z_{ow})$; $B = h_d/\beta_{ow}$; $C = (1 - \rho_{ro})(z_{ao} - z_{ow} + h_d/\beta_{ao}\rho_{ro})$; $D = \rho_{ro}(z_u - z_{ao})$; and $E = h_d/\beta_{ao}$.

Remediation of LNAPL in the subsurface entails extracting as much LNAPL as possible via hydraulic means followed by secondary recovery of residual LNAPL. During the secondary recovery stage, long-term water pumpage and/or gas venting may be employed with or without bioreclamation practices to remove dissolved and/or gaseous LNAPL components. Accurate estimates of the LNAPL spill or leak volume is crucial to the design of an efficient remedial operation.

Table 2 compares predicted LNAPL specific volumes as a function of well hydrocarbon thickness for the two hypothetical soils using methodology proposed in this paper and methods of Hall *et al.* (1984) and de Pastrovich *et al.* (1979). To estimate the hydrocarbon specific volume corresponding to stipulated well hydrocarbon thicknesses using our proposed method, the quasi-static model parameters (Table 1) were employed in (20). Hydrocarbon specific volumes were estimated by the methods of Hall *et al.* and de Pastrovich *et al.* as the product of LNAPL soil thickness and soil effective porosity [i.e., $\phi(1 - S_m)$] which accounts for an "irreducible" water saturation. For the method of Hall *et al.*, soil LNAPL thickness is calculated by subtracting a formation factor, which accounts for capillary fringe effects estimated from median grain size, from well hydrocarbon thicknesses. According to Hall *et al.*, both of the hypothetical soils (i.e., median grain size of 0.2 mm) are classified as fine sands for which the formation factor is 12.5 cm. For the method of de Pastrovich

Table 2. Predicted LNAPL Specific Volumes from Well Hydrocarbon Thicknesses

Well hydrocarbon thickness (cm)	Predicted LNAPL specific volumes ($cm^3\ cm^{-2}$)			
	Hall et al.	*Pastrovich* et al.	*Lenhard and Parker* BC	*Lenhard and Parker* VG
Soil 1				
30	6.5	2.8	0	0.2
60	17.8	5.6	0.3	1.6
100	32.7	9.4	5.7	6.7
150	51.4	14.0	16.7	17.2
200	70.1	18.7	30.0	30.3
250	88.8	23.4	59.7	60.7
Soil 2				
30	3.2	1.4	1.5	1.5
60	8.6	2.7	4.8	4.7
100	15.8	4.5	10.0	9.9
150	24.8	6.8	17.0	17.0
200	33.9	9.0	24.4	24.5
250	42.9	11.3	39.7	40.0

et al., soil LNAPL thickness is estimated to be one-fourth the well hydrocarbon thickness. Multiplying soil LNAPL thickness by the effective porosity presumes the common misconception that water saturations in the contaminated LNAPL zone are equal to a residual or "irreducible" water content and the remaining pores are filled with oil (i.e., "oil pancake").

Since neither the Hall *et al.* or de Pastrovich *et al.* methods account for changes in pore-size distributions, they both predict identical soil LNAPL thicknesses for Soils 1 and 2 (Table 2) and the difference in hydrocarbon specific volumes for the two soils is due to differences in the "irreducible" water saturation. The method of Hall *et al.* generally estimates considerably larger hydrocarbon specific volumes for both soils than either the proposed method or that of de Pastrovich *et al.* for a given well hydrocarbon thickness. The method of de Pastrovich *et al.*, however, predicts larger hydrocarbon specific volumes than the proposed method for small well LNAPL thicknesses and smaller specific volumes for large well hydrocarbon thicknesses for Soil 1. For Soil 2, the method of de Pastrovich *et al.* estimates smaller hydrocarbon specific volumes than the proposed method. Agreement between predicted hydrocarbon volumes for methods of Hall *et al.* and de Pastrovich *et al.* is poor. Considering the importance of soil pore-size distribution in controlling the vertical distribution of fluids, attempting to predict LNAPL volumes without accounting for these effects may be expected to yield poor results. Furthermore, multiplying the *true* soil LNAPL thickness by an assumed effective porosity (i.e., volume of voids not filled with water) will yield overestimates of LNAPL specific volume since water saturation above the water-saturated capillary fringe will actually decrease more or less gradually with elevation. The change in water saturation with elevation is a function of soil pore-size distribution and oil-water capillary head. Water saturations will only approach a step-like function if the soil pores are very uniform in size. The popular notion of predicting LNAPL specific volume from soil LNAPL thickness assuming step-function fluid distributions—"oil pancakes"—is unfounded theoretically and doomed to yield poor results.

To further evaluate the problem of estimating hydrocarbon specific volume from well hydrocarbon thickness, it is expedient to introduce a parameter which we will refer to as the LNAPL reduction factor defined by

$$R = V_o/H_o \tag{24}$$

which permits conversion from observation well LNAPL thickness to LNAPL specific volume. Effects of soil type and well LNAPL thickness on R were analyzed by determining $R(H_o)$ for the two soils previously discussed over a range of H_o typically encountered in the field. The results are shown in Figure 5 for quasi-static conditions using both the VG and BC models. Note that R varies markedly with H_o and in a highly nonlinear manner which is very soil-specific, clearly indicating that simple conversion schemes to relate well LNAPL thickness to total LNAPL volume in porous media are doomed to fail miserably.

It may be shown that in the limit as H_o becomes very large, $R \rightarrow \phi(1 - S_m)$. For the quasi-static fluid distribution of Soil 2 (Figure 5), R is already approaching its limiting value [i.e., $\phi(1 - S_m) = 0.18$] at $H_o = 2$ m. The rate of change of R with respect to H_o is dependent on the slope of the water-saturation curve with respect to elevation. As S_w approaches S_m, the change in R with respect to H_o will be small and will approach $\phi(1 - S_m)$. The principal cause for nonuniform R is the variable water saturation within the LNAPL contaminated zone which depends on the pore-size distribution of the soil.

Calculated values of R using both the VG and BC models agree very favorably for large H_o. At lower H_o there is a significant disparity in predicted

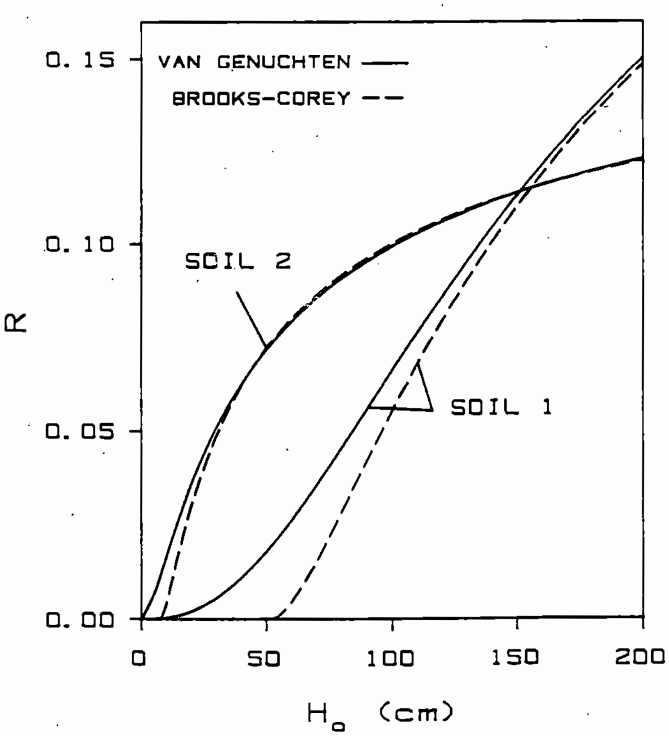

Fig. 5. Relationship between the total LNAPL reduction factor, R, as determined via the van Genuchten and Brooks-Corey models and LNAPL thickness in observation wells, H_o, for quasi-static fluid distributions.

values which may be attributed to the assumption of a distinct nonwetting entry capillary head in the BC model. Note that the difference in predicted R between the VG and BC models at a given H_o is less for Soil 2 which has a lower air entry capillary head, h_d. Also notice that the curves describing $R(H_o)$ using the BC model intersects the x-axis at some $H_o > 0$, whereas R calculated using the VG model approaches zero as H_o approaches zero. This occurs because for the BC model to predict $V_o > 0$, the following condition must be met

$$H_o > \frac{h_d\,[\beta_{ao}\,\rho_{ro} - \beta_{ow}(1-\rho_{ro})]}{\beta_{ow}(1-\rho_{ro})\,\beta_{ao}\,\rho_{ro}} \qquad (25)$$

which can be derived from (8) and (14) by equating S_w and S_t.

Other Complicating Factors

Although we have explicitly considered only homogeneous porous media, the foregoing methodology of calculating oil volumes in soils from observations of fluid levels in monitoring wells can be applied also to layered media. In this case, integration of (20) would simply need to take into account variations in soil properties with elevation. Such an analysis is straightforward in principle but may be thwarted in practice by incomplete knowledge of spatial variation in soil properties. As a result of soil heterogeneity, $R(H_o)$ may exhibit discontinuities and other complex behavior.

In addition to being adaptable to heterogeneous media, the methodology described above also can be refined to consider effects of nonunique S-P relations. It has long been known that the direction of fluid saturation changes has a significant effect on hydrostatic fluid distributions. This phenomenon is commonly referred to as hysteresis. Kool and Parker (1987) found that main drainage and main imbibition S-P relations can be described reasonably well with the VG model using the same value of n for both curves and with α for the imbibition branch, α_i, equal to twice the value of α for the main drainage branch, α_d. Thus, a first approximation of the effects of the effects of hysteresis on hydrocarbon distribution may be made by suitable adjustment of the value of α used for computing saturation distributions.

Let us assume that the quasi-static parameters employed previously represent main drainage relations (i.e., $\alpha = \alpha_d$), and that the previous field scenarios correspond accordingly to conditions of decreasing water and total liquid saturation paths (e.g., falling water table). Consider now the case of water and total liquid both on imbibition paths (e.g., rising water table), for which we use $\alpha_i = 2\alpha_d$ in the expressions for S_w and S_t. For the corresponding BC analysis, we employ new values of h_d for the imbibition path obtained by conversion of VG parameters in the same manner as before. For Soil 1 with a well LNAPL thickness, H_o, of 1 m, the falling water-table scenario yields total LNAPL specific volumes, V_o of 6.7 cm for the VG model and 5.7 cm for the BC model. For the rising water-table scenario with the same H_o, we obtain V_o = 15.2 cm for the VG model and 15.0 cm for the BC analysis. Thus, for the same soil and the same well fluid levels, imbibition relations lead to estimates of LNAPL volume which are more than twice those obtained using drainage relations. As a result, hysteresis will be evident in $R(H_o)$, further complicating the interpretation of observation well data.

The foregoing analysis of hysteretic effects on predicted LNAPL volumes is rudimentary since we have not considered effects of residual LNAPL caused by slow approach to vertical equilibrium or to nonwetting fluid entrapment. During periods of rising water tables, significant volumes of hydrocarbon may become trapped within the continuous water phase (Lenhard *et al.*, 1988c). This hydrocarbon, being hydraulically discontinuous, will have no effect on well fluid levels. During periods of falling water tables, trapped LNAPL may become remobilized leading to increases in well LNAPL thickness. In principle, these effects may be accommodated by incorporation of appropriate descriptions of fluid entrapment in the three-phase S-P relations, but in practice, difficulties will arise owing to uncertainty in saturation histories of the system.

SUMMARY AND CONCLUSIONS

A procedure has been described for estimating hydrocarbon volume per surface area of aquifer in porous media from measured fluid levels in observation wells. The well fluid levels are assumed to be in equilibrium with the fluid distributions within the surrounding porous medium. Hydrocarbon and water saturation profiles are predicted via three-phase versions of the Brooks-Corey and van Genuchten models after converting fluid levels in observation wells to air-oil-water vertical head distributions with assuming vertical equilibrium pressure distributions. Integration of the oil saturation profile yields the hydrocarbon volume corresponding to specified fluid levels. Knowledge of air-water saturation-pressure relations, hydrocarbon density, and hydrocarbon surface tension is required to predict vertical three-phase fluid distributions. Procedures are discussed for estimating air-water saturation-pressure relations from grain-size distribution data.

Effects of grain-size distribution on hydrocarbon distributions and volumes are investigated. Whereas the distance above the oil-water table at which oil saturations become zero may be independent of soil type, estimated LNAPL volumes in different soils will vary substantially. Estimates of LNAPL volume cannot be inferred directly from soil LNAPL thickness or well LNAPL thickness data without consideration of effects of soil properties.

The relationship between well LNAPL thickness and LNAPL reduction factor, which is the ratio of LNAPL specific volume in the porous medium to LNAPL thickness in a well, was studied. The results reveal that no simple linear conversion scheme can be employed to relate the height of LNAPL in an observation well to a LNAPL volume in porous media. LNAPL reduction factors resulting from the Brooks-Corey and van Genuchten models agree favorably for larger well LNAPL thicknesses. There are disparities in predicted LNAPL reduction factors from the Brooks-Corey and van Genuchten models for smaller well LNAPL thicknesses which is attributable to the assumption of a distinct nonwetting entry pressure head in the Brooks-Corey model. Consideration of possible effects of hysteresis in saturation-pressure relations indicates that these may be substantial. Uncertainty in whether drainage or imbibition relations pertain can lead to large differences in predicted hydrocarbon specific volumes.

Finally, we note that the analysis presented here is predicated on the assumption that soil and well fluids are locally in equilibrium with each other. Highly transient flow conditions associated with rapid water-table fluctuations or to bailing of well fluids could invalidate this assumption in certain circumstances. Effects of such nonequilibrium conditions should be further assessed in the future.

APPENDIX

D_o = greatest elevation at which oil saturation is nonzero;

g = gravitational acceleration;

h_j = water-height equivalent pressure head of fluid j (i.e., $P_j/\rho_w g$);

h_{ij} = fluid i,j capillary head (i.e., $h_{ij} = h_i - h_j$) where fluid i is the nonwetting fluid and fluid j is the wetting fluid;

H_o = thickness of hydrocarbon in monitoring well at equilibrium (well hydrocarbon thickness);

h_d = parameter in the Brooks-Corey (1966) model function termed the air entry capillary head;

K = fluid hydraulic conductivity at a given fluid contents;

K_s = saturated water hydraulic conductivity;

m = van Genuchten model parameter; $m = 1 - (1/n)$;

n = van Genuchten model parameter;

P_j = pressure of fluid j;

R = total LNAPL reduction factor;

S_j = actual saturation of fluid j;

$\bar{S}_j$ = effective saturation of fluid j;

S_m = minimum or "irreducible" actual wetting phase saturation;

$S^*(h^*)$ = scaled saturation-pressure function;

V_o = total LNAPL volume per surface area of soil or aquifer (hydrocarbon specific volume);

z = elevation;

z_u = elevation of soil surface with respect to a datum below or equal to z_{ow};

z_{aw} = elevation where water pressure is zero;

z_{ao} = elevation where LNAPL pressure is zero;

z_{ow} = elevation where LNAPL and water pressures are equal;

z_{fao} = elevation below which the porous medium is completely liquid saturated according to the Brooks-Corey model;

z_{fow} = elevation below which the porous medium is completely water saturated according to the Brooks-Corey model;

α = van Genuchten model parameter;

β_{ao} = air-oil scaling factor;

β_{ow} = oil-water scaling factor;

Γ = minimum of z_{fao} or z_u;

λ = Brooks-Corey model parameter;

ρ_j = density of fluid j;

ρ_{ro} = oil specific gravity (i.e., ration of oil to water density);

σ_{ij} = interfacial tension between fluids i and j;

ϕ = porosity;

ψ_j = piezometric head of fluid j; and

subscripts a, o, w refer to air, hydrocarbon, and water phases, respectively.

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Editor's Note: *This paper deals with the identical subject as the paper by A. M. Farr, R. J. Houghtalen, and D. B. McWhorter in this issue. The work was done by the two groups of researchers simultaneously but with no knowledge of the other group's work. The papers were submitted within two weeks of each other in the latter part of 1988. After significant review and revision, both original pieces of work were deemed appropriate for publication inasmuch as the subject is of significant importance in ground-water hydrology, and the duplicate effort clearly enhances the validity of the work as well as its future impact.*

APPENDIX F
ALLIED FIBERS FRANKFORD PLANT EXCAVATION STANDARD OPERATING PROCEDURES

MAINTENANCE PROCEDURES MANUAL	TITLE: EXCAVATION AND SOIL HANDLING PROCEDURE -DRAFT-	PROCEDURE #: MNT-SFT-001-00
WRITTEN BY: D FAIRCHILD	APPROVED BY:	

PURPOSE

1. THIS PROCEDURE PROVIDES A GUIDELINE FOR THE PERFORMANCE OF EXCAVATION TASKS, AND THE HANDLING OF SOIL IN COMPLIANCE WITH ALL OSHA AND ENVIRONMENTAL REGULATIONS CURRENTLY IN EFFECT.

SCOPE

1. ANY EXCAVATION, UNDERGROUND REPAIR, OR CONSTRUCTION WORK MUST CONFORM TO ALL APPLICABLE PLANT REGULATIONS, AND MUST BE PERFORMED AS OUTLINED IN THIS PROCEDURE.

2. ALL EXCAVATIONS MUST COMPLY WITH OSHA STANDARD 1926, SUBPART P.

3. SOIL CONDITION AND DISPOSAL METHOD SHALL BE DETERMINED BY THE ENVIRONMENTAL DEPARTMENT.

DEFINITIONS

1. BENCHING - A METHOD OF PROTECTING EMPLOYEES FROM CAVE-INS BY EXCAVATING THE SIDES OF AN EXCAVATION TO FORM ONE OR A SERIES OF STEPS, USUALLY WITH NEAR VERTICAL SURFACES BETWEEN LEVELS.

2. CAVE-IN - THE SEPARATION OF EARTH FROM THE SIDE OF AN EXCAVATION, EITHER BY FALLING OR SLIDING, IN SUFFICIENT QUANTITY SO THAT IT COULD ENTRAP, BURY, OR OTHERWISE INJURE OR IMMOBILIZE A PERSON.

3. EXCAVATION - A MAN MADE CUT, TRENCH, CAVITY, OR DEPRESSION IN THE EARTH SURFACE, FORMED BY THE REMOVAL OF EARTH.

4. SHORING - A STRUCTURE SUCH AS A METAL, MECHANICAL, TIMBER SYSTEM THAT SUPPORTS THE SIDES OF AN EXCAVATION AND IS DESIGNED TO PREVENT CAVE-INS.

5. SLOPING - A METHOD OF PROTECTING EMPLOYEES FROM CAVE-INS BY FORMING THE SIDES IN AN INCLINED MANNER.

SAFETY & HEALTH

1. PROPER PROTECTION OF INVOLVED EMPLOYEES, SURROUNDING EMPLOYEES, AND THE ADJACENT COMMUNITY MUST BE ENSURED PRIOR TO THE START OF AN EXCAVATION, AND THROUGHOUT ITS DURATION.

ENVIRONMENTAL IMPACT

1. ALL SOIL REMOVED FROM THE GROUND MUST BE HANDLED AS HAZARDOUS WASTE UNLESS DETERMINED OTHERWISE BY THE ENVIRONMENTAL

DEPARTMENT.

2. NO HAZARDOUS WASTE SOIL MAY BE PLACED ON THE GROUND. ONCE REMOVED FROM THE EXCAVATION, IT MUST BE PLACED IN THE APPROPRIATE CONTAINERS FOR DISPOSAL.

3. ALL HAZARDOUS WASTE MUST BE DISPOSED OF AS DIRECTED BY THE ENVIRONMENTAL DEPARTMENT. THIS MATERIAL MAY NOT BE REUSED TO BACKFILL THE EXCAVATION.

4. EFFORTS SHOULD BE MADE TO MINIMIZE THE AMOUNT OF WATER IN THE CONTAINERS. FREE WATER IS NOT ALLOWED IN THE LANDFILL AND TREATMENT IS REQUIRED AT AN ADDITIONAL COST. WATER ALSO ADDS TO THE TOTAL WEIGHT WHICH ALSO INCREASES DISPOSAL COST.

PROCEDURE

1. MAINTENANCE FOREMAN OR ENGINEER IN CHARGE OF THE JOB SHALL FILL OUT EXCAVATION PERMIT AND OBTAIN APPROVALS PER PLANT PROCEDURE.

2. EQUIPMENT REQUIRED FOR SOIL DISPOSAL SHOULD BE LOCATED AT OR NEAR THE JOB SITE PRIOR TO THE INITIATION OF THE EXCAVATION.

3. EMPLOYEES PERFORMING WORK SHOULD BE INFORMED OF THE EXPECTED CONDITION OF THE SOILS EXPOSED.

4. CONTAMINATED SOIL REMOVED FROM THE EXCAVATION MUST BE TRANSFERRED IMMEDIATELY INTO A PLASTIC LINED DUMPSTER OR DRUMS FOR DISPOSAL. USE OF AN INTERMEDIATE TRANSFER DUMPSTER OR TRUCK IS PERMITTED PROVIDING THAT LEAKAGE IS NOT ALLOWED. CONTAINERS SHOULD BE COVERED AT ALL TIMES WHEN WATER ENTRY IS POSSIBLE.

5. IF EVIDENCE OF AN ODOR OCCURS, STOP WORK AND HAVE THE AREA TESTED BY ENVIRONMENTAL DEPT. FOR HAZARDOUS VAPORS. IF EXPOSURE LIMITS ARE EXCEEDED, THEN THE ENVIRONMENTAL AND MAINTENANCE DEPT'S WILL DETERMINE THE BEST METHOD FOR CONTAINMENT BASED ON THE CONDITIONS. REMEDIATION METHODS COULD INCLUDE, BUT ARE NOT LIMITED TO, FLOODING WITH WATER, COVERING WITH SAND OR STONE, LAYERING WITH PLASTIC, ETC.

5. ANY PERSON WHO ENTERS A CONTAMINATED OPENING MUST WEAR AS A MINIMUM, TYVEK SUITS, GLOVES, AND RUBBER BOOTS.

6. IF AN EXCAVATION EXCEEDS THREE(3) FEET IN DEPTH, AND ENTRY IS REQUIRED, THEN SHORING OR SLOPING MUST BE UTILIZED. THE METHOD USED SHOULD COMPLY WITH THE STANDARD DESIGNS FROM OSHA STD 1926, SUBPART P, APPENDIX A,B,C. IN ADDITION, A TANK ENTRY PERMIT MUST BE OBTAINED PER PLANT ENTRY PERMIT PROCEDURES.